

# Spin-dependent $\bar{p}d$ cross sections at low and intermediate energies

Yu N Uzikov<sup>1</sup> and J Haidenbauer<sup>2</sup>

<sup>1</sup>Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, 141980 Dubna, Russia

<sup>2</sup>Institute for Advanced Simulation and Jülich Center for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany

E-mail: uzikov@nusun.jinr.ru

**Abstract.** Antiproton-deuteron ( $\bar{p}d$ ) scattering is calculated at beam energies below 300 MeV within the Glauber approach, utilizing the amplitudes of the Jülich  $\bar{N}N$  models. A good agreement is obtained with available experimental data on unpolarized differential and integrated  $\bar{p}d$  cross sections. Predictions for polarized total  $\bar{p}d$  cross sections are presented, obtained within the single scattering approximation including Coulomb-nuclear interference effects. It is found that the total longitudinal and transversal  $\bar{p}d$  cross sections are comparable in absolute value to those for  $\bar{p}p$  scattering. The kinetics of polarization buildup is considered.

## 1. Introduction

The preparation of an intense beam of polarized antiprotons is *the* crucial point for the physics program proposed by the PAX collaboration [1] at the future FAIR facility in Darmstadt. A possibility to overcome this experimental challenge is seen in elastic scattering of antiprotons off a polarized  $^1\text{H}$  target [2]. This conjecture is motivated by the result of the FILTEX experiment [3], where a sizeable effect of polarization buildup was achieved in a storage ring by scattering of unpolarized protons off polarized hydrogen atoms at low beam energies of 23 MeV. Recent theoretical analyses [4, 5, 6] suggest that the polarization effect observed in Ref. [3] is solely due to the spin dependence of the hadronic (proton-proton) interaction, which gives rise to the so-called spin-filtering mechanism, i.e. leads to different rates of removal of beam protons from the ring for different polarization states of the hydrogen target. Contrary to what was assumed before [7], proton scattering on the polarized electrons of hydrogen atoms does not provide sizeable effects for the polarization buildup [4, 5]. Accordingly, only the hadronic interaction of antiprotons with nucleons or nuclei can be used to produce polarized antiprotons on the basis of the spin-filtering mechanism [4]. Since the spin-dependent part of the  $\bar{p}N$  interaction is still poorly known experimentally, the polarization buildup mechanism in elastic scattering of stored antiprotons off a polarized  $^1\text{H}$  target is planned to be studied in a new experiment at CERN [8, 9] at intermediate energies. Some theoretical estimations of the expected polarization effects were already presented, based on the amplitudes of the Paris [10] and Jülich [11, 12]  $\bar{N}N$  potential models and the Nijmegen [13]  $\bar{N}N$  partial-wave analysis.

In this context, it is important to explore other antiproton–nucleus interactions as possible source for the antiproton polarization buildup too. Therefore, we present here results of a study of polarization effects in antiproton-deuteron ( $\bar{p}d$ ) scattering for beam energies up to 300

MeV [11]. Besides the issue of polarization buildup for antiprotons,  $\bar{p}$  scattering on a polarized deuteron, if it will be studied experimentally, can be also used as a test for our present knowledge of the  $\bar{p}n$  and  $\bar{p}p$  interactions. Our investigation is based on the Glauber-Sitenko theory for  $\bar{p}d$  scattering and it utilizes the  $\bar{N}N$  interaction models developed by the Jülich group [14, 15] as input for the elementary amplitudes.

## 2. Spin dependence of the total $\bar{p}d$ cross section

Considering the full spin dependence of the forward  $\bar{p}d$  elastic scattering amplitude [16, 11] and using the optical theorem, one can show that the total polarized  $\bar{p}d$  cross section can be written as

$$\sigma_{tot} = \sigma_0 + \sigma_1 \mathbf{P}^{\bar{p}} \cdot \mathbf{P}^d + \sigma_2 (\mathbf{P}^{\bar{p}} \cdot \mathbf{m})(\mathbf{P}^d \cdot \mathbf{m}) + \sigma_3 P_{zz}, \quad (1)$$

where  $\mathbf{P}^{\bar{p}}$  is the polarization of the antiproton beam and  $\mathbf{P}^d$  ( $P_{zz}$ ) is the vector (tensor) polarization of the deuterium target,  $\sigma_0$  is the unpolarized and  $\sigma_i$  ( $i = 1, 2, 3$ ) are the polarized total cross sections. The unit vector  $\mathbf{m}$  is fixed by the direction of the beam momentum. One can find from Eq. (1) that only the cross sections  $\sigma_1$  and  $\sigma_2$  are connected with the spin-filtering mechanism [11] and, thus, determine the rate of the polarization buildup in the scattering of unpolarized antiprotons off polarized deuterons. The tensor cross section  $\sigma_3$  is not related to the polarization of the beam and, therefore, is not relevant for the spin-filtering. However, this cross section, as well as the unpolarized cross section  $\sigma_0$ , determine the lifetime of the beam.

We utilize the Glauber theory of multiple scattering [17] for investigating the  $\bar{p}d$  scattering process. For the elementary  $\bar{p}N$  amplitudes we use those of the Jülich models A and D [14, 15]. Details on the applied formalism can be found in Ref. [11]. In order to check the reliability of this approach we calculate the unpolarized total and differential  $\bar{p}d$  cross sections where we can compare our results with available experimental information.

In the evaluation of the polarized cross sections  $\sigma_i$  ( $i = 1, 2, 3$ ), we take into account the Coulomb-nuclear interference terms, which are added to the corresponding purely hadronic cross sections. The pure Coulomb amplitude does not contribute to  $\sigma_i$ ,  $i = 1, 2, 3$ , but it gives an important contribution to  $\sigma_0$ . In order to calculate the contribution of the Coulomb-nuclear interference terms one cannot use the optical theorem because of the Coulomb singularity at the scattering angle  $\theta = 0^\circ$ , and therefore we use here the method of Ref. [4], adapted for the case of  $\bar{p}d$  scattering [11]. For the polarized cross sections we use only the single-scattering approximation.

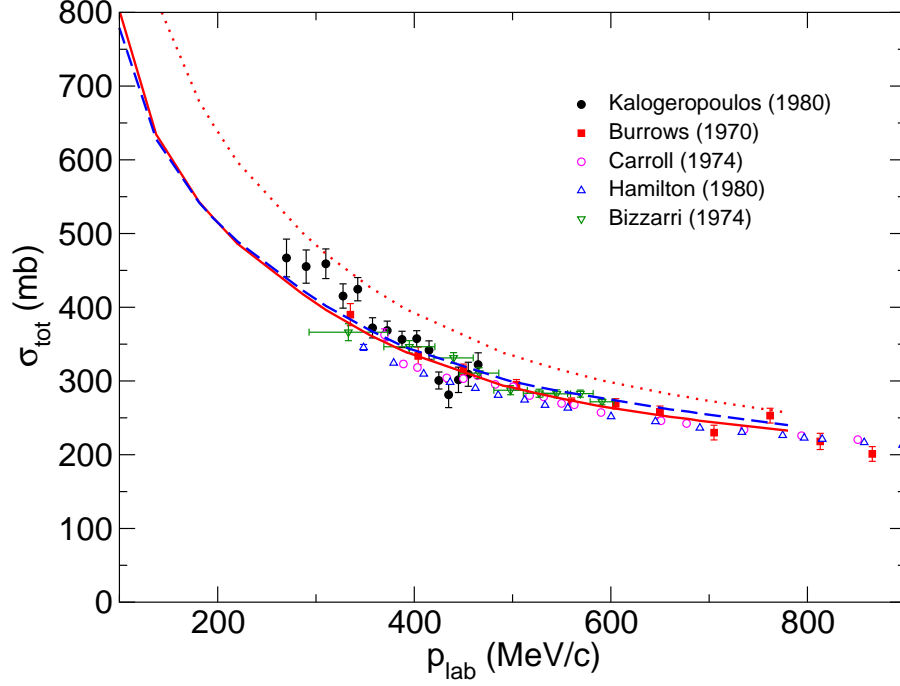
## 3. Results and discussion of $\bar{p}d$ scattering

As was shown in Refs. [18, 19], in forward elastic scattering of antiprotons off nuclei the Glauber theory of diffractive multiple scattering, though in principle a high-energy approach, works rather well even at fairly low antiproton beam energies. The reason for this is that due to strong annihilation effects, the  $\bar{p}N$  elastic differential cross section is peaked in forward direction already at rather low energies and, therefore, suitable for application of the eikonal approximation, which is the basis of the Glauber theory.

The elastic spin-averaged  $\bar{p}N$  scattering amplitude can be parameterized as

$$f_{\bar{p}N}(q) = \frac{k_{\bar{p}N} \sigma_{tot}^{\bar{p}N} (i + \alpha_{\bar{p}N})}{4\pi} \exp(-\beta_{\bar{p}N}^2 q^2 / 2), \quad (2)$$

where  $\sigma_{tot}^{\bar{p}N}$  is the total unpolarized  $\bar{p}N$  cross section,  $\alpha_{\bar{p}N}$  is the ratio of the real to imaginary part of the forward amplitude  $f_{\bar{p}N}(0)$ ,  $\beta_{\bar{p}N}^2$  is the slope of the diffraction cone,  $q$  is the transferred 3-momentum, and  $k_{\bar{p}N}$  is the  $\bar{p}N$  cms momentum. We use Eq. (2) to represent the scattering amplitudes of the Jülich  $\bar{N}N$  models in analytical form. When performing the fit we found that



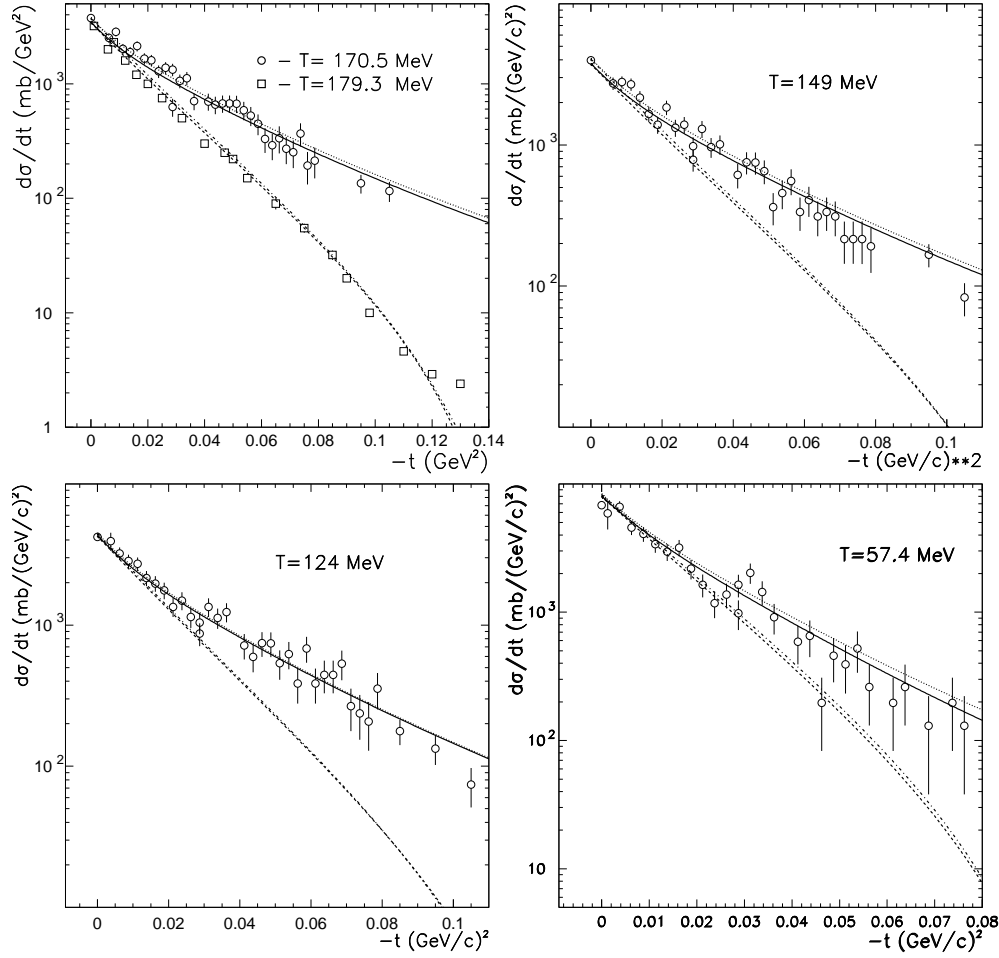
**Figure 1.** Total  $\bar{p}d$  cross section versus the beam momentum  $p_{lab}$ . The solid and dashed lines are results based on the  $\bar{N}N$  models D and A, respectively. The dotted line is the results for model D obtained within the single-scattering approximation. Data are taken from Refs. [20, 21, 22, 23, 24].

even at beam energies as low as 10-25 MeV the parameter  $\beta_{\bar{p}N}^2$  is large, i.e.  $40 - 50 \text{ (GeV/c)}^2$ , reflecting the fact that the  $\bar{p}N$  amplitude is indeed peaked in forward direction.

Results for the total unpolarized  $\bar{p}d$  cross section are displayed in Fig. 1 together with experimental information [20, 21, 22, 23, 24]. One can see that the single-scattering approximation (shown here for model D only) overestimates the total unpolarized cross section by roughly 15%, cf. the dotted line. But the shadowing effect generated by  $\bar{p}N$  double scattering reduces the cross section (solid line) and leads to a good agreement with the experiment. The results for model A (including also double scattering) are very similar (dashed line) and also in agreement with the data.

Predictions for differential cross sections are presented in Fig. 2. Also here the single-scattering mechanism as well as the double-scattering terms were included in the corresponding calculation. The ABB form factor [25] is used for the deuteron. At  $T_{lab} = 179.3 \text{ MeV}$  data for the elastic differential cross section are available [26]. These data (squares in Fig. 2) are nicely reproduced by our model calculation for forward angles. Also the differential cross sections for elastic ( $\bar{p}d \rightarrow \bar{p}d$ ) plus inelastic ( $\bar{p}d \rightarrow \bar{p}pn$ ) scattering events, measured at the neighboring energy of  $T_{lab} = 170 \text{ MeV}$  as well as at some lower energies [20] (circles), are well described.

Results for the spin-dependent  $\bar{p}d$  cross sections  $\sigma_1$  and  $\sigma_2$  are obtained in the single-scattering approximation and presented in Fig. 3 (right-hand side). We show predictions based on the purely hadronic part,  $\sigma_i^h$ , as well as full results, including the Coulomb-nuclear interference term, i.e.  $\sigma_i = \sigma_i^h + \sigma_i^{int}$  for  $i = 1, 2$ . The  $\bar{N}N$  model D predicts large values for  $\sigma_1$  around 40 MeV and for  $\sigma_2$  around 25 MeV. In case of model A the most pronounced spin dependence is

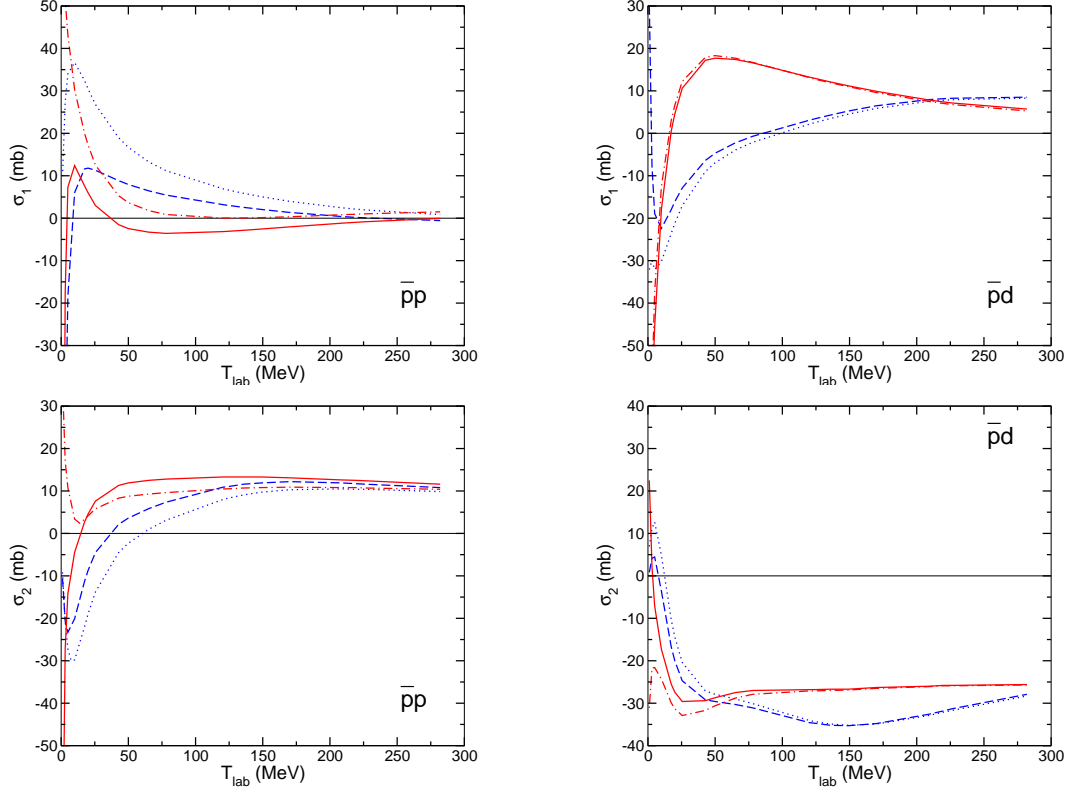


**Figure 2.** Elastic (lower lines) and elastic plus inelastic (upper lines)  $\bar{p}d$  differential cross sections versus the transferred momentum for different antiproton beam energies. The lines are results of a calculation based on the Glauber theory for model A (dotted and dashed-dotted) and D (solid and dashed) utilizing the parameterizations of the  $\bar{p}N$  amplitudes via Eq. (2) as given in Ref. [11]. Data are taken from Ref. [26] (179.3 MeV, squares) and from Ref. [20] (57.4–170.5 MeV, circles).

seen at considerably higher energies.

Compared with the results for the  $\bar{p}p$  reaction, shown on the left-hand side of Fig. 3, the spin-dependent  $\bar{p}d$  cross sections  $\sigma_1$  and  $\sigma_2$  are of similar magnitude or even larger. With regard to the purely hadronic contribution,  $\sigma_i^h$  ( $i=1,2$ ), the cross sections for  $\bar{p}p$  and  $\bar{p}d$  are, in general, of opposite sign [11]. It should be said, however, that the sign does not affect the spin-filtering mechanism. The effect of the Coulomb-nuclear interference is somewhat smaller for  $\bar{p}d$  scattering than for the  $\bar{p}p$  case. This difference comes from the additional  $\bar{p}n$  amplitudes entering the expression for  $\sigma_i^{int}$  in case of the  $\bar{p}d$  reaction, cf. Ref. [11] for details.

One can see from Fig. 3 that the largest values for the polarized  $\bar{p}d$  cross sections (and also those for  $\bar{p}p$ ) are expected at very low energies, i.e. for  $T_{lab}$  less than 10 MeV, where the cross sections are dominated by the Coulomb-nuclear interference term. However, as was already mentioned above, at these energies the pure Coulomb cross section becomes rather large, so that the method of spin-filtering for the polarization buildup cannot be applied due to the decrease



**Figure 3.** Total spin-dependent cross sections  $\sigma_1$  and  $\sigma_2$  versus antiproton laboratory energy  $T_{lab}$  for  $\bar{p}p$  (left column) and  $\bar{p}d$  (right column) scattering. Results based on the purely hadronic amplitude,  $\sigma_i^h$ , (model D: dash-dotted line, model A: dotted line) and including the Coulomb-nuclear interference term, i.e.  $\sigma_i = \sigma_i^h + \sigma_i^{int}$ , (D: solid line, A: dashed line), are shown.

of the beam lifetime.

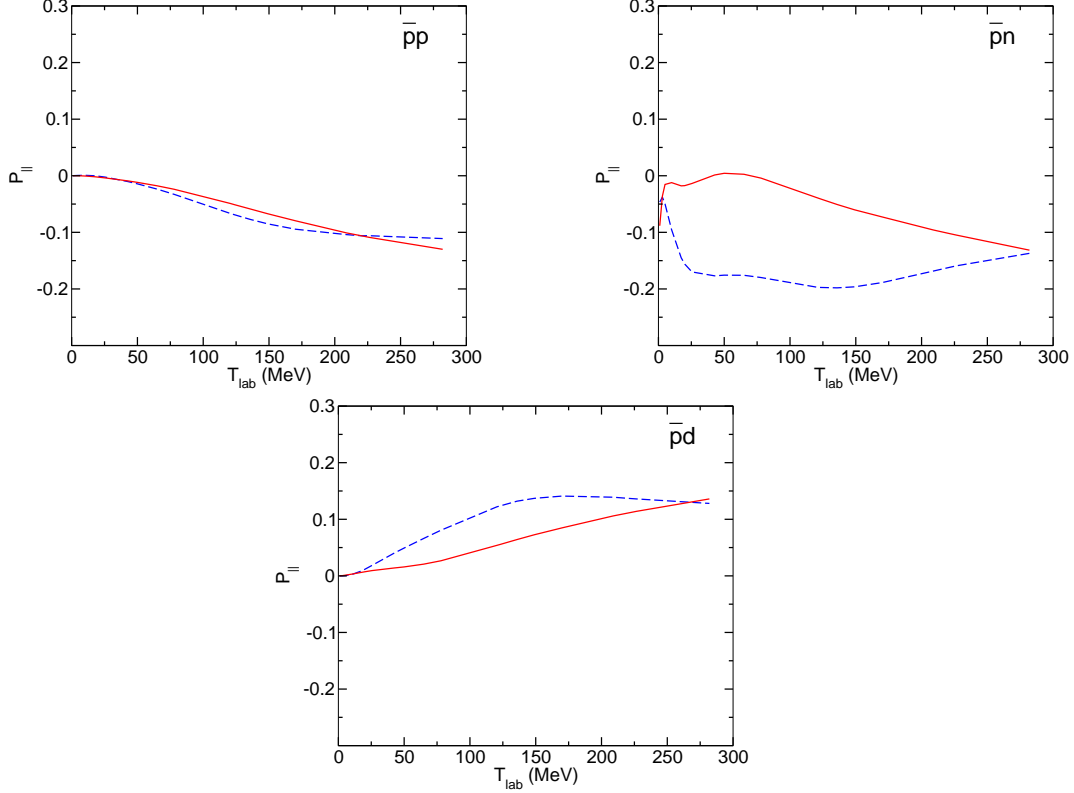
According to the analysis of the kinetics of polarization [4, 6], the polarization buildup is determined mainly by the ratio of the polarized total cross sections to the unpolarized one ( $\sigma_0$ ) [4]. Let us define the unit vector  $\boldsymbol{\zeta} = \mathbf{P}_T/P_T$ , where  $\mathbf{P}_T = \mathbf{P}^d$  is the target polarization vector, which in the case of  $\bar{p}d$  scattering enters Eq. (1). The non-zero antiproton beam polarization vector  $\mathbf{P}^{\bar{p}}$ , produced by the polarization buildup, is collinear to the vector  $\boldsymbol{\zeta}$  for any directions of  $\mathbf{P}_T$  and can be calculated from consideration of the kinetics of polarization. The general solution for the kinetic equation for  $\bar{p}p$  scattering is given in Ref. [4]. Here we assume that this solution is valid for the  $\bar{p}d$  scattering also. Therefore, for the spin-filtering mechanism of the polarization buildup the polarization degree at the time  $t$  is given by [4, 13]

$$P_{\bar{p}}(t) = \tanh \left[ \frac{t}{2} (\Omega_-^{out} - \Omega_+^{out}) \right], \quad (3)$$

where

$$\Omega_{\pm}^{out} = n f \left\{ \sigma_0 \pm P_T \left[ \sigma_1 + (\boldsymbol{\zeta} \cdot \mathbf{m})^2 \sigma_2 \right] \right\}. \quad (4)$$

Here  $n$  is the areal density of the target and  $f$  is the beam revolving frequency. One should note that the tensor cross section  $\sigma_3$  from Eq. (1) does not contribute to  $\Omega_{\pm}^{out}$ . Assuming the condition  $|\Omega_-^{out} - \Omega_+^{out}| \ll (\Omega_-^{out} + \Omega_+^{out})$ , which was found in Refs. [4, 13] for the  $\bar{p}p$  scattering in rings at  $n = 10^{14} \text{ cm}^{-2}$  and  $f = 10^6 \text{ c}^{-1}$ , one can simplify Eq. (3). If one denotes the number of antiprotons in the beam at the time moment  $t$  as  $N(t)$ , then the figure of merit (FOM) is



**Figure 4.** Dependence of the longitudinal polarization  $P_{||}$  (i.e.  $P_{\bar{p}}(t_0)$  for  $\boldsymbol{\zeta} \cdot \mathbf{m} = 1$ ) on the beam energy for the target polarization  $P_T = 1$  in the different reactions  $\bar{p}p$ ,  $\bar{p}n$ , and  $\bar{p}d$ . The results are for the model A (dashed line) and D (solid line). The acceptance angle in the cms is  $\theta_{acc} = 10$  mrad.

$P_{\bar{p}}^2(t)N(t)$ . This value is maximal at the moment  $t_0 = 2\tau$ , where  $\tau$  is the beam life time, which is determined by the total cross section  $\sigma_0$  of the interaction of the antiprotons with the deuteron target as

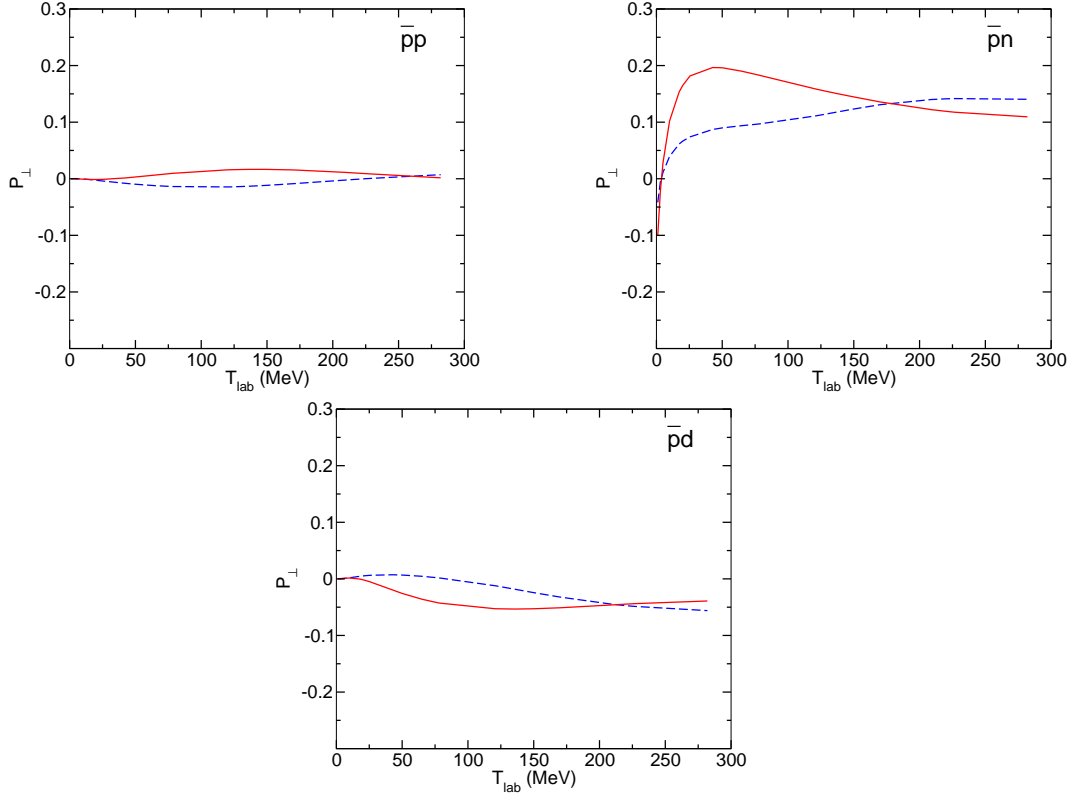
$$\tau = \frac{1}{nf\sigma_0}. \quad (5)$$

To estimate the efficiency of the polarization buildup mechanism it is instructive to calculate the polarization degree  $P_{\bar{p}}$  at the time  $t_0$  [13]. In our definition for  $\sigma_1$  and  $\sigma_2$ , which differ from that in Refs. [4, 13], we find

$$\begin{aligned} P_{\bar{p}}(t_0) &= -2P_T \frac{\sigma_1}{\sigma_0}, \text{ if } \boldsymbol{\zeta} \cdot \mathbf{m} = 0, \\ P_{\bar{p}}(t_0) &= -2P_T \frac{\sigma_1 + \sigma_2}{\sigma_0}, \text{ if } |\boldsymbol{\zeta} \cdot \mathbf{m}| = 1, \end{aligned} \quad (6)$$

The polarization degree  $P_{\bar{p}}(t_0)$  for  $\boldsymbol{\zeta} \cdot \mathbf{m} = 1$  ( $P_{||}$ ) at  $P_T = P^d = 1$  is shown in Fig. 4 versus the beam energy. For the ease of comparison the polarization degree for the  $\bar{p}p$  and  $\bar{p}n$  cases are shown too. The results for  $\boldsymbol{\zeta} \cdot \mathbf{m} = 0$  ( $P_{\perp}$ ) are shown in Fig. 5.

One can see that, except for the  $\bar{p}n$  case, at energies below 100 MeV the polarization degree is small due to large total Coulomb cross section. However,  $P_{\bar{p}}(t_0)$  increases with increasing energy. For longitudinal polarization maximal values of about 10-15% are predicted above 150 MeV. The transversal polarization degree is smaller than the longitudinal one for both models



**Figure 5.** Dependence of the transversal polarization  $P_{\perp}$  (i.e.  $P_{\bar{p}}(t_0)$  for  $\zeta \cdot \mathbf{m} = 0$ ) on the beam energy for the target polarization  $P_T = 1$  in the different reactions  $\bar{p}p$ ,  $\bar{p}n$ , and  $\bar{p}d$ . The results are for the model A (dashed line) and D (solid line). The acceptance angle in the cms is  $\theta_{acc} = 10$  mrad.

A and D. For the  $\bar{p}d$  case the transversal polarization is expected to be larger than for  $\bar{p}p$ , having a maximum of around 5% at 150 -250 MeV (see Fig. 5). The obtained values for the polarization degree are somewhat smaller than those presented in [13], based on the amplitudes of the Nijmegen  $\bar{N}N$  analysis [27]. Experiments for determining the spin-dependent part of the cross sections of the  $\bar{p}p$  and  $\bar{p}d$  scattering are planned for the near future [8, 9]. Such data should allow one to discriminate between the different  $\bar{N}N$  amplitudes [13, 11].

#### 4. Conclusion

In this work we have used two  $\bar{N}N$  potential models developed by the Jülich group for a calculation of  $\bar{p}d$  scattering within the Glauber theory and found that this approach allows one to describe the experimental information on (unpolarized) differential and total  $\bar{p}d$  cross sections, available at  $T_{lab} = 50 - 180$  MeV, quantitatively. For those spin-independent observables the difference in the predictions based on those two models turned out to be rather small.

The double-scattering corrections to the unpolarized cross section were found to be in the order of 15% in the energy range where the data are available. But we found that even at such low energies as 10-25 MeV they are not larger than 20-25%. This means that, most likely, the Glauber approximation does work reasonably well for  $\bar{p}d$  scattering down to fairly small energies.

The predictions for the spin-dependent cross sections for  $\bar{p}d$  scattering, presented in this work, exhibit a fairly strong model dependence, which is due to uncertainties in the spin dependence of the elementary  $\bar{p}p$  and  $\bar{p}n$  interactions. Still, for both considered models we find that the magnitude of the spin-dependent cross sections is comparable or even larger than those for  $\bar{p}p$ .

Thus, our results suggest that  $\bar{p}d$  elastic scattering can be used for the polarization buildup of antiprotons at beam energies of 100-300 MeV with similar and possibly even higher efficiency than  $\bar{p}p$  scattering. However, it is obvious, that only concrete experimental data on the spin-dependent part of the cross sections of  $\bar{p}p$  and  $\bar{p}d$  scattering will allow one to confirm or disprove the feasibility of the spin filtering mechanism for the polarization buildup.

### Acknowledgements

This work was supported in part by the Heisenberg-Landau program.

### References

- [1] Barone V *et al* [PAX Collaboration] 2005 arXiv:0505054[hep-ex]
- [2] Rathmann F *et al* 2005 *Phys. Rev. Lett.* **94** 014801
- [3] Rathmann F *et al* 1993 *Phys. Rev. Lett.* **71** 1379
- [4] Milstein A I and Strakhovenko V M 2005 *Phys. Rev. E* **72** 066503
- [5] Nikolaev N N and Pavlov F 2005 arXiv:0512051[hep-ph]
- [6] Nikolaev N N and Pavlov F 2007 *AIP Conf. Proc.* **915** 932
- [7] Meyer H O 1994 *Phys. Rev. E* **50** 1485
- [8] Lenisa P and Rathmann F [PAX Collaboration] 2005 arXiv:0512021[nucl-ex].
- [9] Barschel C *et al* [PAX Collaboration] 2009 arXiv:0904.2325[nucl-ex]
- [10] Dmitriev V F, Milstein A I and Strakhovenko V M 2008 *Nucl. Instrum. Meth. B* **266** 1122
- [11] Uzikov Yu N and Haidenbauer J 2009 *Phys. Rev. C* **79** 024617
- [12] Haidenbauer J, contribution to this conference.
- [13] Dmitriev V F, Milstein A I and Salnikov S G 2010 *Phys. Lett. B* **690** 427; Salnikov S G, contribution to this conference.
- [14] Hippchen T, Haidenbauer J, Holinde K and Mull V 1991 *Phys. Rev. C* **44** 1323; Mull V, Haidenbauer J, Hippchen T and Holinde K 1991 *Phys. Rev. C* **44** 1337
- [15] Mull V and Holinde K 1995 *Phys. Rev. C* **51** 2360
- [16] Rekalov M P, Piskunov N M and Sitnik I M 1998 *Few-Body Syst.* **23** 187
- [17] Franco V and Glauber R J 1966 *Phys. Rev.* **142** 1195
- [18] Kondratyuk L A, Shmatikov M Zh and Bizzarri R 1981 *Yad. Fiz.* **33** 795 [1981 *Sov. J. Nucl. Phys.* **33** 413 ]
- [19] Dalkarov O D and Karmanov V A 1985 *Nucl. Phys. A* **445** 579
- [20] Bizzarri R *et al* 1974 *Nuovo Cim.* **22 A** 225
- [21] Kalogeropoulos T and Tzankos G S 1980 *Phys. Rev. D* **22** 2585
- [22] Burrows R D *et al* 1970 *Austr. J. Phys.* **23** 919
- [23] Carroll A S *et al* 1974 *Phys. Rev. Lett.* **32** 247
- [24] Hamilton R P *et al* 1980 *Phys. Rev. Lett.* **44** 1182
- [25] Aladashvili B S *et al* 1977 *J. Phys. G* **3** 7
- [26] Bruge G *et al* 1988 *Phys. Rev. C* **37** 1345
- [27] Timmermans R, Rijken T A and de Swart J J 1994 *Phys. Rev. C* **50** 48